NORMAL SPECTRAL EMISSIVITY AT A WAVELENGTH OF 684.5 nm AND THERMOPHYSICAL PROPERTIES OF SOLID AND LIQUID MOLYBDENUM [1]

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ABSTRACT

Normal spectral emissivity is an important quantity for temperature determination when measuring thermophysical properties, but it is a difficult task to determine normal spectral emissivity under pulse heating conditions in the liquid state. A laser polarimeter for the determination of optical parameters without any moving parts was adapted for pulse heating experiments, which are performed in a sub-microsecond time-scale, and integrated into the existing measurement setup.

The behaviour of normal spectral emissivity for liquid metals at 684.5 nm was discovered by our measurements to fit into three groups of a) decreasing, b) constant, or c) increasing emissivity-values as a function of temperature in the beginning of the liquid phase. Molybdenum i.e. belongs to group a) of the above classification, as it shows a very slight decrease of normal spectral emissivity with temperature. The correspondingly same behaviour for electrical resistivity (under initial geometry) can be found, as suggested by the Hagen-Rubens-Relation for the IR range. Thermophysical properties of the liquid metals obtained, using the actual measured values, can change drastically in comparison to those obtained with the assumption of a constant emissivity in the liquid state, if the change in emissivity during the liquid state is significant. To achieve more reliable thermophysical properties of liquid metals, measurements of normal spectral emissivity in combination with pyrometric temperature determination are needed.

Within this paper polarimetric emissivity measurements adapted for a rapid pulse heating setup and recent results of normal spectral emissivity at 684.5 nm for Molybdenum at melting and in the liquid phase are presented as well as a complete set of thermophysical data for Molybdenum in the solid and the liquid state, which are compared to literature values.

1. INTRODUCTION

Thermophysical data of pure metals and alloys have been widely studied to support on one hand the metal working industry or to provide them as input for computer simulations, and on the other hand, for a better scientific understanding of different physical processes. These days casting simulations have become a very powerful and almost irreplaceable tool in the design process and the preproduction modeling of new parts i.e. for the automobile industry. Therefore, a constant need for even more and more accurate thermophysical data arise for the known materials, as well as there is always a constant need for data of newly used alloys such as Ti-aluminides or magnesium based alloys.

Our workgroup has been measuring such thermophysical properties for a long period of time now and always tries to enhance data for already measured materials (even our own measurements) as well as to have a focus on new alloys like Ti-Al-Nb-B [1] and up to now unspecified metals.

The data presented within this paper belong to the first category, because thermophysical properties of solid and liquid Molybdenum have been published already earlier [2], but we expanded our range of accessible properties to thermal conductivity and thermal diffusivity of Molybdenum, which have not been published before.

The latest and probably most innovative addition in our range of measured properties is normal spectral emissivity at a wavelength of 684.5 nm. These emissivity data are also used for computer simulations, because the determination of emissivity up into the liquid state has always been a difficult task. Therefore, literature data are not easily available and a constant need exists for those measurements.

The thermophysical properties presented within this paper have been determined using a resistive pulse-heating technique, which has been proven to produce reproducible and accurate measurement from the solid state (some hundred Kelvin below the melting point) up into the liquid phase. Additionally, we incorporated DSC (Differential-Scanning-Calorimetry) measurements into our set of data obtaining enthalpy versus temperature starting from almost room temperature (~ 500 K) up to a maximum temperature of about 1500 K. The values obtained with this technique can not only be used to amend our enthalpy and heat capacity measurements but can also be used to expand our temperature range down into the solid state. [3]

Normal spectral emissivity measurements have been performed with a laser polarimetry technique (µs-DOAP), which is one of the few available techniques to obtain emissivity data in the liquid state under pulse-heating conditions. Due to the use of a laser as the light source, our emissivity measurements are limited to the initial wavelength (684.5 nm) of the laser.

2. EXPERIMENT SETUP AND DATA REDUCTION

2.1 Pulse Heating Setup
The basic principle behind this technique is to pass a large current pulse over a wire shaped specimen (typically 0.5 mm diameter), which causes a rapid increase in the temperature due to the resistance of the material under investigation. In our case, we obtain heating rates of about 10^8 K/s which result in an average experimental duration ob about 30 – 60 µs per single measurement. See [4] for more specific detail of the

pulse-heating system used in Graz. (A schematic overview of the experiment can be seen in Fig. 1.)
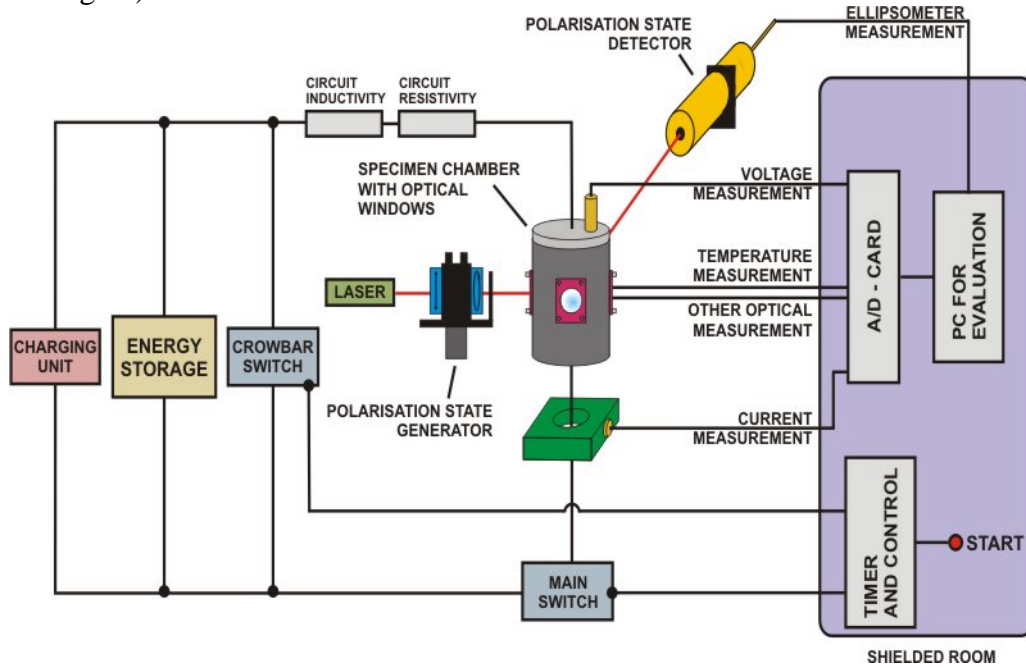

Fig. 1: Schematic sketch of the pulse-heating setup including the DOAP experiment in Graz.

Data Reduction
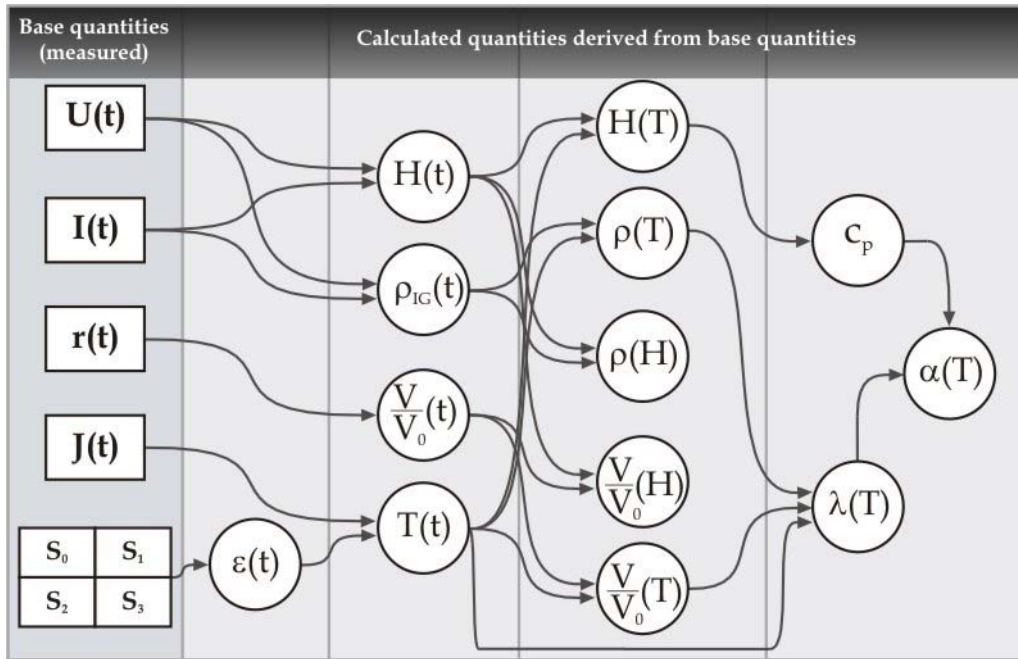
Fig. 2: Schematic drawing of directly measured and calculated quantities. U…voltage, I…current, r…specimen radius, J…surface radiation, s_0-s_3…Stokes parameters, ε…emissivity, H…enthalpy, ρ_{IG}…electrical resistivity (initial geometry), V/V_0…volume expansion, T…temperature, ρ…electrical resistivity (referred to in text as ρ_{Vol}), c_p…specific heat capacity, a…thermal diffusivity, λ…thermal conductivity.

The directly measured quantities during such a pulse-heating experiment consist of the current, *I(t)*, through the specimen wire measured with a calibrated induction coil (Pearson Electronics, Inc.), the voltage drop, *U(t)*, across the specimen determined by means of two knife-edge probes and the surface radiation of the wire by means of a fast optical pyrometer. Starting with these four measured quantities all other thermophysical data can be calculated shown in Fig. 2.

TEMPERATURE

Temperature is one of the most important quantities to be determined in all thermophysical properties investigations. Temperature is calculated based on the pyrometrically determined surface radiation of the sample by using Planck's radiation law. To minimize the uncertainty arising from the wavelength in Planck's law, narrow interference filters have to be used in the pyrometers. Therefore, each pyrometer is only designed for a specific temperature range (based on the IF-filter and the photodiode used) and is generally not sensitive to temperatures below 1200 K - 1500 K [3]. The radiation temperature of the sample is obtained using the voltage output of a calibrated pyrometer:

$$T_{Rad} = \frac{c_2}{\lambda \cdot \ln\left(\frac{K}{S} + 1\right)} \qquad (1)$$

where S is the output signal of the pyrometer, T_{Rad} the radiation temperature of the sample at the effective wavelength λ of the pyrometer. K is the calibration-factor of the pyrometer-system, and c_2 the second radiation constant. The true sample temperature T can be obtained with the help of Planck's law by the following equation:

$$T = \frac{c_2}{\lambda} \cdot \frac{1}{\ln\left[\varepsilon \cdot \left(e^{\frac{c_2}{\lambda \cdot T_{Rad}}} - 1\right) + 1\right]} \qquad (2)$$

where ε is the normal spectral emissivity at the wavelength λ. As one can see, the actual value of the normal spectral emissivity at the wavelength of the pyrometer is needed for this procedure.

If the temperature dependency of normal spectral emissivity is not explicitly known, a constant emissivity value in the liquid phase had to be assumed for temperature evaluations [5].

ENTHALPY AND RESISTIVITY

The voltages used in the calculations are the measured values corrected for inductive contributions. The specific enthalpy, *H(t)*, is calculated from *U(t)* and *I(t)*, starting at room temperature (although the temperature measurement starts at higher temperatures):

$$H(t) = \frac{1}{m} \cdot \int I(t) \cdot U(t) \cdot dt \qquad (3)$$

where m is the mass of the sample.

The electrical resistivity under consideration of the initial geometry ρ_{IG}, may be calculated by:

$$\rho_{IG}(t) = \frac{U(t) \cdot \pi \cdot r^2}{I(t) \cdot \ell} \qquad (4)$$

where r is the sample radius at room temperature, and ℓ the length of the specimen. For further evaluation the change in volume has to be taken into consideration for electrical resistivity, ρ_{Vol}, as the specimen wire expands during the heating process. ρ_{Vol} is basically obtained by multiplying ρ_{IG} by $V/V_0(T)$.

THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY

Thermal conductivity λ may be estimated from temperature dependent electrical resistivity ρ_{Vol} by using the Wiedemann - Franz - Law (W-F-L) in its well known form:

$$\lambda(T) = \frac{L \cdot T}{\rho_{Vol}(T)} \qquad (5)$$

where T is temperature, and L the Lorentz number, $L = 2.45 \cdot 10^{-8}$ V^2/K^2 assuming that the Lorentz number is invariant within the region of interest. Based on thermal conductivity, thermal diffusivity a may be estimated from specific heat capacity at constant pressure c_p and density $d(T)$:

$$a(T) = \frac{\lambda(T)}{c_p(T) \cdot d(T)} \qquad (6)$$

2.2 Differential Scanning Calorimetry (DSC)

The DSC is primarily used to measure temperature dependencies of the specific heat capacity (under constant ambient pressure) $c_p(T)$. By integrating the specific heat capacity values, the enthalpy can be directly calculated (with regard to the value H_{298} at RT). Therefore, $H(T)$ for the solid state starting at the DSC onset temperature at about 500 K up to 1500 K can obtained. This dependency can be used to assign a temperature scale to the electrical measured quantities during a pulse heating experiment (i.e. enthalpy, resistivity) below the pyrometer onset temperature. More details are given in [3].

2.3 μs-Division-Of-Amplitude-Photopolarimeter (μs-DOAP)

Normal spectral emissivity at 684.5 nm is measured by using a so called Division-Of-Amplitude-Photopolarimeter. The DOAP uses an ellipsometric measurement approach but without any rotating devices in regard to the timescale used for a pulse-heating experiment. This technique has first been described by Azzam [6] and uses the Stokes formalism for polarized light.

Basically, a polarized laser beam is focused on the surface of the sample wire and the change in polarization of the reflected beam is analyzed. For more details see [7, 8].

Data Reduction for DOAP

The detected signals are split into four intensities (hence the name Division-Of-Amplitude) from which the complex refractive index n and the extinction coefficient κ

for the sample material are calculated. These two quantities are used to determine normal spectral reflectivity at the given wavelength by the following equation:

$$R = \frac{(n - n_0)^2 + \kappa^2}{(n + n_0)^2 + \kappa^2} \qquad (7)$$

where n_0 is the refractive index of the ambient medium. Finally, normal spectral emissivity can easily calculated for opaque materials by using Kirchoff's law:

$$\varepsilon(\lambda) = 1 - R(\lambda). \qquad (8)$$

Further details on µs-DOAP assisted emissivity measurements are given in [8].

3. MEASUREMENTS AND RESULTS

All measurements within this work have been performed on wire shaped Molybdenum specimens with a diameter $\varnothing = 0.5$ mm and an average length of about 70 mm total (50 mm active length). The material was purchased by Goodfellow Cambridge Limited with the following specifications: Diameter: 0.5 mm, Purity: 99.95%, Hardness: annealed. Additionally, for emissivity measurements a Molybdenum wire from Plansee ($\varnothing = 0.5$ mm, Purity: n/a, Surface: electro polished) was used also for comparison reasons, whereas thermophysical properties were only measured using the wire from Goodfellow.

3.1 Results

All graphs given within this section represent averages of different measurements. For thermophysical properties six independent measurements (the deviation between each of the single experiments was better than 1%) have been used to obtain the averaged results. For normal spectral emissivity eight independent measurements have been used due to weaker signal to noise ratio. Corresponding with [9], a melting temperature of $T_m = 2896$ K used for all evaluations.

NORMAL SPECTRAL EMISSIVITY
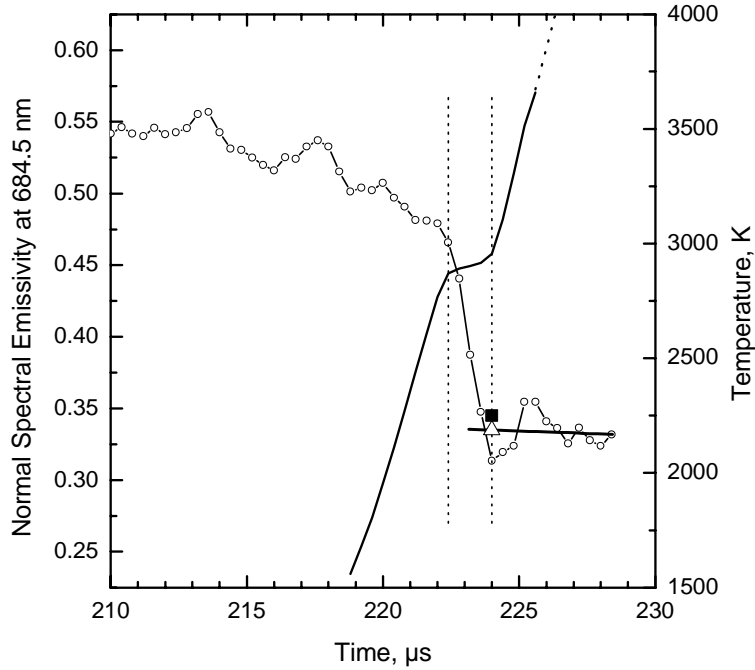
Fig. 3: Normal spectral emissivity at 684.5 nm and temperature of Molybdenum as a function of time. Open circles: emissivity (average of eight measurements); full line: temperature signal; vertical dotted lines: begin and end of the melting transition; open triangle: literature value of [10]; full square: reference value of [11].

Fig. 3 shows normal spectral emissivity of Molybdenum in the liquid state. The linear least-squares fit for the liquid phase is:

$$\varepsilon(T) = 0.3375 - 1.0093 \cdot 10^{-6} \cdot T \qquad 2896 \text{ K} < T < 4000 \text{ K} \qquad (9)$$

At the end of melting, emissivity is $\varepsilon(T_m) = 0.334$.

ENTHALPY

<u>Fig. 4:</u> Specific enthalpy of Molybdenum as a function of temperature. Open circles: values obtained by pulse-heating; open triangles: values obtained wit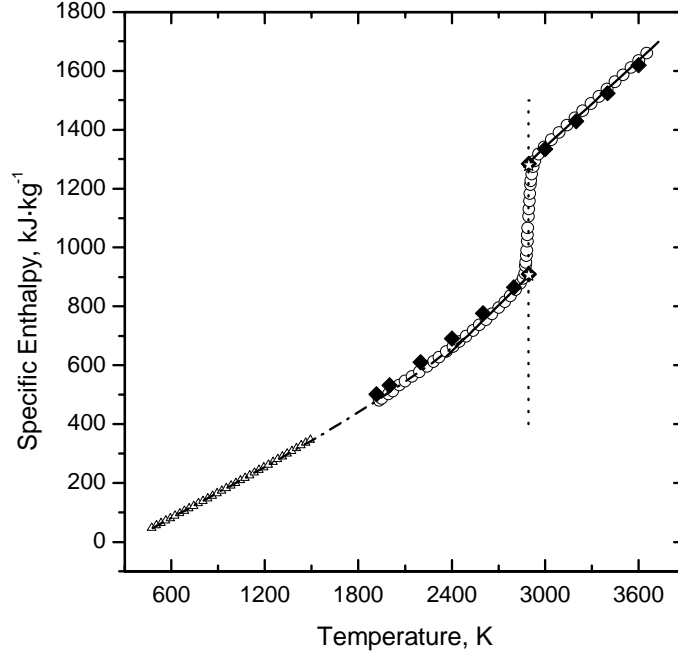h DSC; full lines: linear least-squares fits to the end of the solid and the begin of the liquid phase; dashed line: fit to the temperature region from 400 K – 2460 K; vertically dotted line: melting temperature; full squares: literature values from [9]; open stars: values from [12].

Fig. 4 presents enthalpy obtained with the pulse heating system as well as with the DSC. The fit for the solid state (combination of DSC and pulse-heating data; 3rd order) and the linear (least-squares) fit for the high temperature region of the solid state are (H in kJ·kg^{-1}):

$$H_s(T) = -98.7046 + 0.3183 \cdot T - 3.8103 \cdot 10^{-5} \cdot T^2 + 1.5336 \cdot 10^{-8} \cdot T^3 \qquad (10)$$
$$480 \text{ K} < T < 2480 \text{ K},$$
$$H_s(T) = -594.6586 + 0.5177 \cdot T \qquad 2480 \text{ K} < T < 2896 \text{ K} \qquad (11)$$

And

$$H_l(T) = -133.7498 + 0.4916 \cdot T \qquad 2896 \text{ K} < T < 3600 \text{ K} \qquad (12)$$

for the liquid state.

At melting, $H_s(T_m) = 904.6$ kJ·kg^{-1} and $H_l(T_m) = 1289.9$ kJ·kg^{-1}; thus we obtain a heat of fusion of $\Delta H = 385.3$ kJ·kg^{-1}. The entropy of fusion calculated by $\Delta S = \Delta H / T_m$ for Molybdenum is $\Delta S = 133.05$ J·kg^{-1}·K^{-1}.

The values for specific heat capacity are obtained from the slope of the linear fits above. At the end of the solid phase a mean value of $c_{p,s} = 517.7$ J·kg^{-1}·K^{-1} is obtained, and a constant value of $c_{p,l} = 491.6$ J·kg^{-1}·K^{-1} was found for the liquid phase.
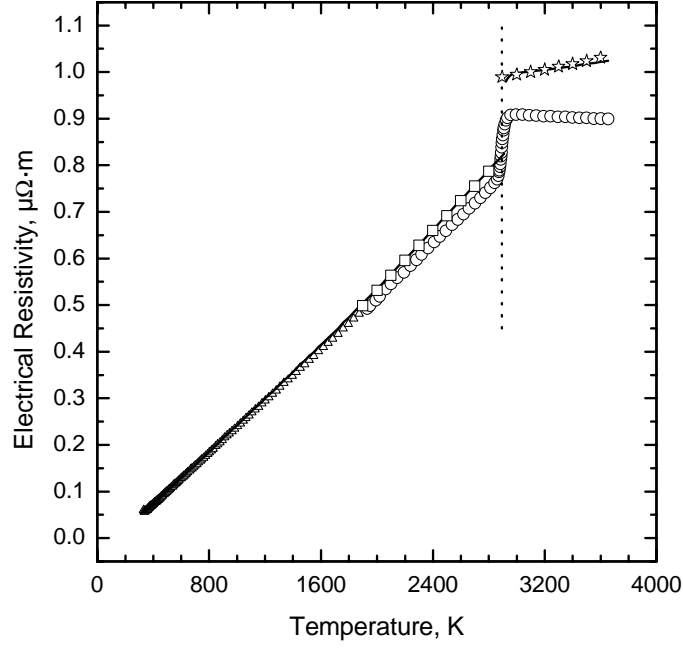
ELECTRICAL RESISTIVITY

Fig. 5: Electrical resistivity (with initial geometry and with consideration of volume expansion) for Molybdenum as a function of temperature. Open circles: data (initial geometry) from pulse-heating measurements; open triangles: pulse-heating data (initial geometry) incorporating the temperature scale from DSC experiments; full line: volume corrected resistivity; vertically dotted line: melting temperature; open squares: literature values from [13]; open stars: values from [9].

Results for both, electrical resistivity with initial geometry as well as values considering volume expansion are presented in Fig. 4. The volume expansion of pure Molybdenum was taken from literature, namely [14] for the solid state and [9] for the liquid state. Note that the resistivity values are shown in the solid state starting from 500 K.

The fits for electrical resistivity with initial geometry (ρ_{IG} in $\mu\Omega\cdot$m) are:

$$\rho_{IG,s}(T) = -0.0384 + 2.8436\cdot10^{-4}\cdot T - 1.0970\cdot10^{-8}\cdot T^2 + 3.6622\cdot10^{-12}\cdot T^3 \qquad (13)$$
$$400\ \text{K} < T < 2896\ \text{K}$$

$$\rho_{IG,l}(T) = 0.9535 - 1.1498\cdot10^{-5}\cdot T \qquad\qquad 2896\ \text{K} < T < 3600\ \text{K} \qquad (14)$$

The resistivity at the onset of melting is $\rho_{IG,s}(T_m) = 0.782$ $\mu\Omega\cdot$m, at the end of melting $\rho_{IG,l}(T_m) = 0.910$ $\mu\Omega\cdot$m. Therefore we obtain an increase in resistivity during melting of $\Delta\rho_{IG} = 0.128$ $\mu\Omega\cdot$m.

The values considering volume correction (ρ_{Vol} in $\mu\Omega\cdot$m) are represented by the following fits:

$$\rho_{Vol,s}(T) = -0.0342 + 2.6770\cdot10^{-4}\cdot T + 6.7741\cdot10^{-9}\cdot T^2 + 9.6354\cdot10^{-13}\cdot T^3 \qquad (15)$$
$$400\ \text{K} < T < 2896\ \text{K}$$

$$\rho_{Vol,l}(T) = 0.8483 + 4.8435\cdot10^{-5}\cdot T \qquad\qquad 2896\ \text{K} < T < 3600\ \text{K} \qquad (16)$$

The resistivity at the onset of melting is $\rho_{Vol,s}(T_m) = 0.821$ $\mu\Omega\cdot$m, at the end of melting $\rho_{Vol,l}(T_m) = 0.989$ $\mu\Omega\cdot$m. Therefore we obtain an increase in volume considered resistivity during melting of $\Delta\rho_{Vol} = 0.168$ $\mu\Omega\cdot$m.
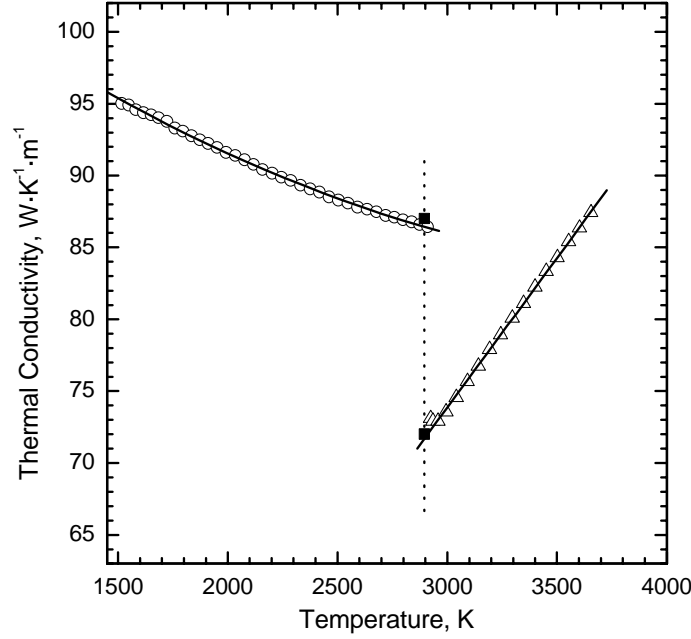
THERMAL CONDUCTIVITY

<u>Fig. 6:</u> Thermal conductivity of Molybdenum as a function of temperature. Open circles: measured data for the solid state; open triangles: data for the liquid state; vertically dotted line: melting temperature; full squares: reference values from [15].

Thermal conductivity (λ in $W \cdot K^{-1} \cdot m^{-1}$) as shown in Fig. 6 in the solid and the liquid phase is represented by the following fits:

$$\lambda_s(T) = 111.1349 - 0.0126 \cdot T + 1.4122 \cdot 10^{-6} \cdot T^2 \qquad (17)$$
$$1500 \text{ K} < T < 2896 \text{ K}$$

$$\lambda_l(T) = 11.4262 + 0.0208 \cdot T \qquad 2896 \text{ K} < T < 3600 \text{ K} \qquad (18)$$

Thermal conductivity at the onset of melting is $\lambda_s(T_m) = 86.4$ $W \cdot K^{-1} \cdot m^{-1}$, at the end of melting $\lambda_l(T_m) = 71.7$ $W \cdot K^{-1} \cdot m^{-1}$. Therefore we obtain an increase in thermal conductivity during melting of $\Delta\lambda = 14.7$ $W \cdot K^{-1} \cdot m^{-1}$.

THERMAL DIFFUSIVITY

Thermal diffusivity of Molybdenum is not given in a separate Figure, as it looks basically same as Fig. 6 and thus adds nothing new. Therefore, the values for thermal diffusivity ($a \cdot 10^{-5}$ $m^2 \cdot s^{-1}$) are only given by the following fit results:

$$a_s(T) = 2.1212 \cdot 10^{-5} - 2.5475 \cdot 10^{-9} \cdot T + 4.2606 \cdot 10^{-13} \cdot T^2 \qquad (19)$$
$$2500 \text{ K} < T < 2896 \text{ K}$$

$$a_l(T) = 1.6210 \cdot 10^{-6} + 4.5065 \cdot 10^{-9} \cdot T \qquad 2896 \text{ K} < T < 3600 \text{ K} \qquad (20)$$

Thermal diffusivity at the onset of melting is $a_s(T_m) = 1.74 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$, at the end of melting $a_l(T_m) = 1.47 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$. Thus we obtain an increase in thermal diffusivity during melting of $\Delta\lambda = 0.27 \cdot 10^{-5}$ $m^2 \cdot s^{-1}$.

Tab. 1: Summary of values for specific enthalpy, H, heat of fusion, ΔH, specific heat capacity, c_p, specific electrical resistivity, ρ, thermal conductivity, λ, and normal spectral emissivity, ε, as reported by different authors. (Index s: solid; index l: liquid; T_m: melting temperature; *…extrapolated to T_m)

Reference	H_s kJ·kg^{-1}	H_l kJ·kg^{-1}	ΔH kJ·kg^{-1}	$c_{p,s}$ J·kg^{-1}·K^{-1}	$c_{p,l}$ J·kg^{-1}·K^{-1}	$\rho_{Vol,s}$ μΩ·m	$\rho_{Vol,l}$ μΩ·m	λ_s W·K^{-1}·m^{-1}	λ_l W·K^{-1}·m^{-1}	$\varepsilon(T_m)$
This work	904.6	1289.9	385.3	517.7	491.6	0.821	0.989	86.4	71.7	0.33 (684.5 nm)
Cezairliyan [13]	-	-	-	523.3*	-	0.818*	-	-	-	-
McClure [16]	-	-	379.4	-	-	-	-	-	-	-
Hixson [9]	909.2	1284.8	375.3	-	475	0.836	0.990	-	-	-
Shaner [12]	907	1280	373	-	-	0.801	0.955	-	-	-
Seydel [17]	888	1393	505	-	500	0.806	0.971	-	-	-
Hultgren [18]	930.1	1296.5	339.4	545.5	357.4	-	-	-	-	-
Pottlacher [19, 2[+]]	910	1320	410	-	540	0.80	0.98	89[+]	72[+]	-
NPL Report [15]	-	-	-	-	-	-	-	87	72	-
Cezairliyan [20]	-	-	-	-	-	-	-	-	-	0.343 (657 nm)
Miiller [10]	-	-	-	-	-	-	-	-	-	0.335 (653 nm)
Cezairliyan [21]	-	-	-	-	-	-	-	-	-	0.342 (633 nm)
Matsumoto [11]	-	-	-	-	-	-	-	-	-	0.345 (633 nm)

4. DISCUSSION

In the following section, specific details concerning each figure will further be discussed. Generally, it can be seen from Fig. 3 – 6 and Tab. 1, that all of our measured values fit very well to different literature references.

Normal spectral emissivity: At the onset of melting a strong decrease in emissivity can be nicely seen in Fig. 3. In the liquid phase, normal spectral emissivity at 684.5 nm of Molybdenum shows a slight decrease up to temperatures of 4000 K. This decrease could also be guessed from the liquid phase behaviour of electrical resistivity with initial geometry if one assumes the validity (to a certain extent) of the Hagen-Rubens-Relation ($\varepsilon \propto f(\rho)$) at this wavelength.

At the end of melting, a value of emissivity of $\varepsilon = 0.33$ is obtained, which seems to fit quite good the available literature data, although the different measurement wavelengths do not match exactly.

Finally, we used Molybdenum wires from two different manufactures; although the values in the solid state were different due to varying surface structures, the specimens from both manufacturers did not only show the same behaviour in the liquid phase but also the same value at melting.

Specific enthalpy: We measured both, enthalpy values in the range from 400 K – 1500 K by DSC and from 1900 K – 3600 K with the pulse heating setup. Although the heating rates are completely different, both data sets agree very well with each other, as can be seen in Fig. 4. This proofs that the pulse heating experiment can be considered quasi-static, as long as there are no solid state phase transitions.

As a result, a combined fit in the temperature range from 400 K – 2460 K is given for Molybdenum. The literature data (where available) fit quite nicely our measured values.

Electrical resistivity: Fig. 5 depicts electrical resistivity with initial geometry as well as electrical resistivity values considering volume expansion. The temperature obtained by DSC measurements of enthalpy has been used to downscale electrical resistivity measured with the pulse heating setup down to ~ 500 K. Although the volume expansion is taken from literature data [9,14], the volume expansion considered resistivity values show an excellent agreement with data reported by other authors.

Thermal conductivity: By using the W-F-L, we calculated thermal conductivity of Molybdenum in the temperature range from 1500 K – 3600 K. A comprehensive literature comparison was not possible, since there are only few data for thermal diffusivity available in this temperature range. Touloukian [22] presents different reference data, but they are very dispersed over the entire range. As there is also no recommendation given, the values are not used for comparison reasons.

Nevertheless, NPL gives recommended values for thermal conductivity of Molybdenum at the melting transition and our measured data show an almost exact match with these NPL values.

Thermal diffusivity: Thermal diffusivity is calculated based on our thermal conductivity values. A separate graph has been omitted, as it shows almost the same behaviour as thermal conductivity. Other than with thermal conductivity, no literature data were available for comparison in the temperature region of interest.

The fit in the solid state ranges only from 2500 K – 2896 K as thermal diffusivity calculations use the specific heat capacity at the given temperature, which can only be obtained at the end of the solid state by pulse heating measurements.

5. CONCLUSION

We have measured a complete set of thermophysical properties of Molybdenum in the solid and the liquid state including uncertainties, which are quoted in the following section. Our measurements are in excellent agreement with literature references (where available). Other than most of the past publications on thermophysical properties of Molybdenum, we also present values for thermal conductivity as well as thermal diffusivity at melting and in the liquid phase.

Additionally, measurements of normal spectral emissivity at 684.5 nm for liquid Molybdenum are presented within the current work. As we found out in previous measurements, the liquid phase behaviour of normal spectral emissivity at 684.5 nm can be categorized into a) decreasing, b) constant, or c) increasing [23]. Molybdenum seamlessly fits into category a) of this classification, as normal spectral emissivity shows a very slight decrease throughout the liquid phase.

Since the change in emissivity during the liquid phase is little, all measurements from other authors without consideration of the actual behaviour of emissivity are not expected to differ significantly from values of this work.

6. ESTIMATION OF UNCERTAINTY

According to the guide to the expression of uncertainty in measurement [24] uncertainties reported here are expanded relative uncertainties with a coverage factor of $k = 2$. Two lists of final evaluated sets of uncertainties are given, first for directly measured variables such as current, I, 2%, voltage drop, U, 2%, temperature, T, 4%, mass, m, 2%.

For the calculated thermophysical properties on obtains the following uncertainties: enthalpy, H, 4%; enthalpy of melting ΔH, 8%, specific heat capacity c_p, 8%, specific electrical resistivity with initial geometry, ρ_{IG}, 4%; resistivity considering volume expansion, ρ_{Vol}, 6%; thermal conductivity, λ, 12%; and thermal diffusivity, a, 16%.

An estimation of uncertainty for normal spectral emissivity, ε, is performed by determining the signal-to-noise ratio of different individual measurements and by analysing the reproducibility of different measurements. For investigations on liquid Molybdenum the signal-to-noise of a single experiment does not exceed 6%. By averaging several different measurements to minimize the noise of the emissivity signals and applying a linear least-squares fit to the liquid phase behaviour of normal spectral emissivity, the uncertainty can be reduced up to a factor of 2, thus yielding an uncertainty of $\pm$ 3%. By including the coverage factor of $k = 2$ one obtains an uncertainty for normal spectral emissivity for liquid Molybdenum of $\pm$ 6%, respectively.

7. ACKNOWLEDGEMENT

8. REFERENCES

[1]   C. Cagran, B. Wilthan, G. Pottlacher, B. Roebuck, M. Wickins and R. A. Harding, results presented at TOFA 2002, Rome, Italy (2002), publication in progress.

[2]   G. Pottlacher, *J. Non-Cryst. Solids,* **250-252**, 177 (1999).

[3]   B. Wilthan, C. Cagran and G. Pottlacher, *A Comparison of Enthalpy Values of Selected Metals Obtained by Pulse-Heating and by Differential-Scanning-Calorimetry*, submitted to 15th Symposium on Thermophysical Properties, Boulder (2003).

[4]   E. Kaschnitz, G. Pottlacher and H. Jäger, *Int. J. Thermophys.*, **13**, 699 (1992).

[5]   G. R. Gathers, *Int. J. Thermophys.*, **4,** 149 (1983).

[6]   R. M. A. Azzam, *Opt. Acta*, **29**, 685 (1982).

[7]   A. Cezairliyan, S. Krishnan, and J. L. McClure, *Int. J. Thermophys.*, **17**, 1455 (1996).

[8]   A. Seifter, F. Sachsenhofer, and G. Pottlacher, *Int. J. Thermophys.*, **23**, 1267 (2002).

[9]   R. S. Hixson and M. A. Winkler, *Int. J. Thermophys.*, **13**, 477 (1992).

[10] A. P. Miiller and A. Cezairliyan, *Temperature – Its Measurement and Control in Science and Industry*, **6**, J. F. Schooley, ed., AIP, 769 (1992).

[11] T. Matsumoto, A. Cezairliyan and D. Basak, *Int. J. Thermophys.*, **20**, 943 (1999).

[12] J. W. Shaner, G. R. Gathers and C. Minichino, *High. Temp. – High. Press.*, **9**, 331 (1977).

[13] A. Cezairliyan, M- S. Morse. H. A. Berman and C. W. Beckett, *J. Res. Nat. Bur. Stand. (US)*, **74A**, 65 (1970).

[14] *Handbook of Thermophysical Properties of Solid Materials, Vol.1 – Elements*, Ed.: A. Goldsmith, T. E. Waterman and H. J. Hirschorn, Pergamon Press, 1961

[15] K. C. Mills, B. J. Monaghan and B. J. Keene, *Thermal Conductivities of Liquid Metals – Part 1: Pure Metals*, NPL Report CMMT(A) 53 (1997).

[16] J. L. McClure and A. Cezairliyan, *Int. J. Thermophys.*, **11**, 731 (1990).

[17] U. Seydel, W. Fucke and H. Wadle, *Die Bestimmung thermophysikalischer Metalle mit schnellen Pulsaufheizexperimenten*, P. Mannhold, Düsseldorf (1980).

[18] R. Hultgren, P. D. Desai, D. T. Hawkins, M. Gleiser, K. K. Kelley and D. D. Wagman, *Selected Values of the Thermodynamic Properties of the Elements*, American Society for Metals, UMI, Reprinted (1990).

[19] G. Pottlacher, E. Kaschnitz and H. Jäger, *J. Non-Cryst. Solids*, **156-158**, 374 (1993).

[20] A. Cezairliyan and A. P. Miiller, *Int. J. Thermophys.*, **14**, 1109 (1993).

[21] A. Cezailriyan, S Krishnan, D. Basak and J. L. McClure, *Int. J. Thermophys.*, **19**, 1267 (1998).

[22] Y. S. Touloukian, R. W. Powell, C.Y. Ho and P. G. Klemens, *Thermal properties of Matter – Volume 1*, New York, Plenum (1970).

[23] C. Cagran, C. Brunner, A. Seifter and G. Pottlacher, *High Temp. High. Press.*, 15th ECTP (2002), paper in print.

[24] Expression of the Uncertainty of Measurement in Calibration, EA-4/02, *http://www.european-accreditation.org/pdf/EA-4-02ny.pdf*